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Investigating Three-Dimensional Effect on Crack Growth Behavior in an Incompressible Material

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Abstract

In order to obtain some insight into the three-dimensional effects on the crack growth behavior, a series of experiments on centrally perforated cylinders under internal pressure were conducted using the frozen stress methods. The inner surface of the cylinder has a star shape, which consists of six fins. Part-through cracks were cut at different locations near the fin tip region. The effect of crack location on the crack growth behavior and the role of shear modes during crack turning were investigated and the results are discussed.

Introduction

An important engineering problem in structural design is evaluating structural integrity and reliability. It is well known that structural strength may be degraded during its design life due to mechanical or chemical aging, or a combination of these two aging mechanisms. Depending on the structural design, material type, service loading, and environmental condition, the cause and degree of strength degradation due to the different aging mechanisms differs. One of the common causes of strength degradation is the result of crack development in the structure. In addition to the development of cracks under service loads, cracks may also develop during the manufacturing of the material. Therefore, in order to determine the structural reliability, the criticality of the crack needs to be determined.

After Cotterell described the concept of Class 1 and Class 2 cracks for two-dimensional problem(1-2), Cotterell and Rice (3) presented an analysis for slightly curved or kinked cracks again for two-dimensional problems , which accounted for the role of Mode II in crack turning. Rubenstein (4), in analyzing test results, concluded that sharpe kinks likely occur only in a very brittle materials, more commonly, the change in direction during crack growth is more of a gradual turning than a kink. Very recently, Leblond (5) provided a three-dimensional framework for use in analyzing problems with linear elastic fracture mechanics constraints when the crack configuration is known. All of the prior authors experience with stably growing cracks had been with Class I problems under pure Mode I loading.

In this study, the frozen stress photoelastic method was used to investigate the three-dimensional effect on the crack growth behavior in a centrally perforated cylinder under internal pressure. The inner surface of the cylinder has a star shape, which consists of six fins. Part-through cracks were cut at different locations near the fin tip region. The effect of crack location on the crack growth behavior and the role of shear modes during crack turning were investigated and the results are discussed.

The Experiments

In order to obtain some insight into the three-dimensional effects on crack growth behavior under load, a series of experiments on pre-cracked centrally perforated cylindrical specimens, made of a photoelastic material, were conducted using the frozen stress method. The starter cracks were made by first drilling a small hole opposite the fin in which the crack is to be located, sliding a shaft with a tip blade into the hole, positioning the blade at the critical point on the fin surface and then striking the shaft with a hammer. The starter cracks then emanated from the blade tip into the materials as "natural" or real cracks. For the crack located at the point of confluence of the small fin edge radius with the larger fin tip surface radius, a short blade was used opposite the main blade to balance the impact load on the shaft. The specimens were capped at the ends and pressurized internally above critical temperature after real cracks were introduced at fin tips in critical locations. After growing to desired size, pressure was reduced to stop growth and held through cooling.

Results and Discussion

Photoelastic analysis of an uncracked pressurized specimen showed that there were two critical locations at a fin tip; one at the confluence of the edge radius of R = 1.3mm with the radius R = 11.0mm of the central part of the fin tip, and the other on the fin axis itself. There are two positions on each fin tip where the confluence of the two above noted radii exist. A crack emanating from such a position we call an off-axis crack. A crack at the other location on a fin axis we call a symmetric crack, which is symmetric with respect to both load and specimen geometry, and is a Class I crack which grows readily. Off-axis cracks however generally do not occupy principal planes of stress or planes of symmetry and are generally called Class II cracks which must turn or kink to eliminate some shear modes before becoming purely Mode I at which time they will grow readily as Class I cracks. By placing both types of cracks in the same model (Fig. 1) separated by uncracked or plugged fins, (plugs are cylinders used to seal holes made to allow the insertion of a shaft which carries a blade to a critical locus at the fin tip), it was confirmed that the symmetric cracks penetrated to the outer surface of the model before the off-axis cracks had grown significantly.

Experimental data also reveal that the turning effect in three dimensional off-axis cracks involves a shear mode except near the fin tip surface and, in non-brittle materials, turns rather than kinks sharply. Upon eliminating the shear mode, pure Mode I occurs all along the crack front in the Class I sense.

Figure 2 shows two off axis (Model 4 and Model 8)), inclined cracks initiated at the point of confluence noted above and normal to the fin surface. Figure 2 (Model 4) shows the early stages of growth where the crack is still turning and exhibits both Modes I and II all around the crack front except at the fin surface where pure mode I exists. Figure 2 (Model 8) shows another crack grown from the same location but much further until only Mode I exists along the crack front. Its turning has been completed as shown by the path of the mid point of the crack. It has just become a Class 1 crack. The Model 4 crack was 8.71 mm deep and 22.3 mm wide after growth compared to 12.5 mm and 42.2 mm for Model 8. River markings on Model 8 show the presence of Mode III as well as Modes I and II during the Class 2 phase of growth. Clearly this crack is not planar.

The river markings, shown in Fig. 2 (Model 8), were produced by light reflections, which indicated a change in the surface level along the markings. The cause of the river markings could come from initial mis-alignment of the blade, bending of the blade when struck, lack of symmetry, or minute inhomogeneity of the model material.

Due to the above findings, and the inherent difficulty in repeating Class 2 growth paths, it was decided to introduce the off-axis starter cracks at the point of confluence of the fin tip radii directed parallel to the fin axis. Four new models, each containing 2 cracks of the above type and located as in Fig. 3, were prepared in this manner and tested by the frozen stress method. Test results reveal that the starter crack quickly grows as a Class I crack with virtually no turning. It also reveal that very few river markings resulted here which suggests that a proliferation of river markings may be partially due to the blade orientation normal to the surface and exacerbated by lack of symmetry, and not only misalignment.

Taken collectively, the above studies suggest the following observations: i) Symmetric cracks are more dangerous than off-axis cracks even though they do not start at the locus of maximum stress in the uncracked model. ii) Off-axis cracks directed parallel to the fin axis are also dangerous but less so than the symmetric cracks for they will grow on slightly curved paths. iii) While some of the cracks penetrated the outer wall in the depth direction, none of the cracks penetrated the length of the cylinder.

These results suggest that the practice of using a through the cylinder length crack in design maybe a substantial over design and suggests a comparison with deep semi-elliptic cracks as an alternative approach.

Conclusion

In this study, the three-dimensional effects on the crack growth behavior in centrally perforated cylindrical specimens with pre-crack were investigated, using stress frozen techniques. Experimental findings reveal that the maximum stress in the uncracked specimen occurs at the confluence of the two tip radii. When cracks of equal depth are placed at the above location and also on the axis of symmetry of a fin, the latter crack always begin to grow sooner and further than the former crack, which inevitably contains shear modes. In other words, when the crack is symmetric in both load and specimen geometry, it will grow far more readily than off-axis cracks due to the shear modes effect, or three-dimensional effect, in the latter even though the stress maybe higher at the off-axis locus in an uncracked fin. Experimental findings also reveal that, after the crack completed its turning, the shear modes are eliminated and the crack grows under pure Mode I loading.

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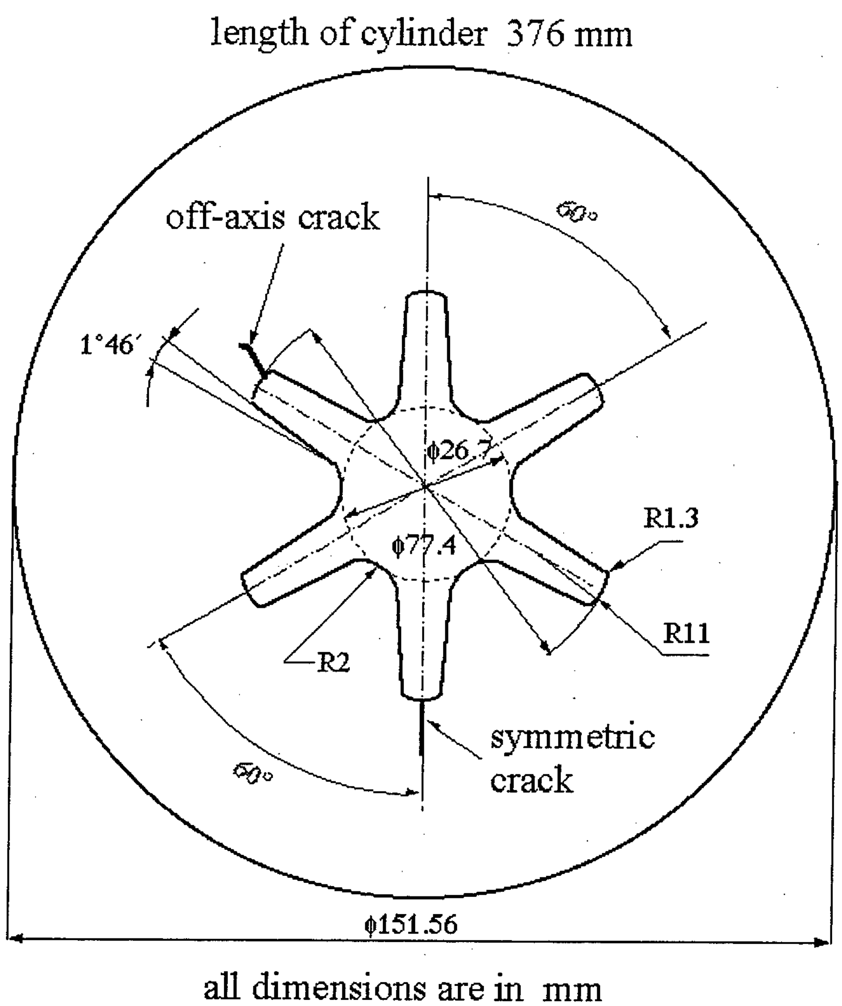
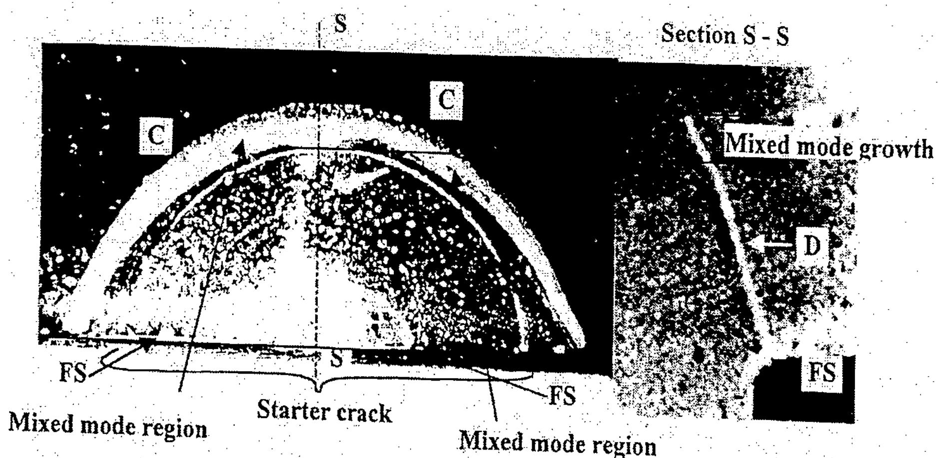
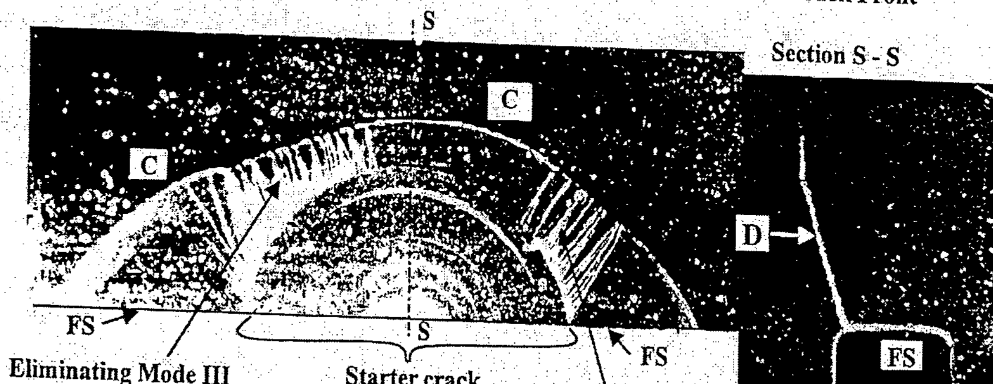


Fig. 1 Specimen Geometry.



magnification factor: 4.22

Model 4 Off-Axis Inclined Crack Showing Starter Crack and Final Crack Front

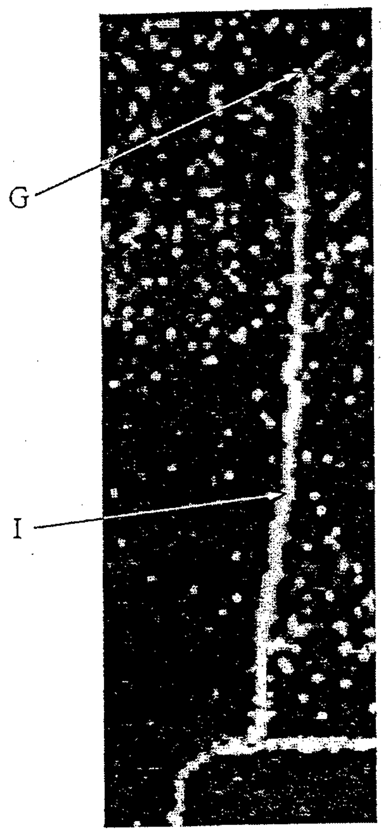


FS – fin surface
C – crack front
D – camera view of the photograph

magnification factor: 2.50

Model 8-i Off-Axis Inclined Crack Showing Starter Crack and Final Mode I Crack Front

Fig. 2 Projected Crack Profiles and Path of Center-Point



I – Initial Crack Tip Location

G – Crack Tip Location after Growth

Fig. 3 Path of Crack Midpoint when Blade is Parallel to Fin Axis